In-Space Internet-Based Communications for Space Science Platforms Using Commercial Satellite Networks

Robert J. Kerczewski, Kul B. Bhasin, Theodore P. Fabian, and James H. Griner
Glenn Research Center, Cleveland, Ohio

Brian A. Kachmar and Alan M. Richard
Analex Corporation, Cleveland, Ohio

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National Aeronautics and
Space Administration

Glenn Research Center

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Robert J. Kerczewski[*], Kul B. Bhasin, Theodore P. Fabian, and James H. Griner
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Brian A. Kachmar[†] and Alan M. Richard
Analex Corporation
3001 Aerospace Parkway
Cleveland, Ohio 44142

ABSTRACT

The continuing technological advances in satellite communications and global networking have resulted in commercial systems that now can potentially provide capabilities for communications with space-based science platforms. This reduces the need for expensive government owned communications infrastructures to support space science missions while simultaneously making available better service to the end users. An interactive, high data rate Internet type connection through commercial space communications networks would enable authorized researchers anywhere to control space-based experiments in near real time and obtain experimental results immediately. A space based communications network architecture consisting of satellite constellations connecting orbiting space science platforms to ground users can be developed to provide this service. The unresolved technical issues presented by this scenario are the subject of research at NASA's Glenn Research Center in Cleveland, Ohio. Assessment of network architectures, identification of required new or improved technologies, and investigation of data communications protocols are being performed through testbed and satellite experiments and laboratory simulations.

INTRODUCTION

In satisfying the need for lower cost and higher performance for space-based research missions, the National Aeronautics and Space Administration (NASA) is moving away from proprietary special purpose, government-owned and operated communications systems. The current and anticipated future growth in commercial satellite communications networks is well timed to provide lower cost alternatives. Many of the planned new systems in low, medium and high earth orbits can provide a range of coverages and data downlink capacities that can potentially meet the needs of a variety of future space missions. Ka-band systems in particular have the potential of providing much higher bandwidth and availability for space science applications without a major government infrastructure investment.

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[*] Phone: (216) 433–3434, Fax: (216) 433–8705, E-mail: rkerczewski@grc.nasa.gov

[†] Phone: (216) 433–8655, Fax: (216) 433–8705, E-mail: bkachmar@grc.nasa.gov

In addition to the anticipated cost reductions obtained using commercially available communications assets, greatly improved performance of future space science missions is also a major goal. A key to improving accessibility, data integrity, and response times to the end user will be the implementation of Internet connectivity between the space-based experimental platform and the experimenter on the ground. An interactive Internet connection would enable authorized researchers in virtually any location to control experimental parameters and retrieve the resulting experimental data.

The feasibility and potential performance of such an Internet connectivity scenario is being explored through laboratory and satellite based research in Internet protocol performance at NASA Glenn, including tests with NASA's Ka-Band Advanced Communications Technology Satellite (ACTS). Key architecture, protocol performance, and technology issues are being identified and active research efforts are underway to enable future space science missions to become orbiting Internet nodes. NASA Glenn is developing the In-Space Internet Node Testbed Facility to enable this research.

As an example of a space-based research platform for which Internet connectivity would provide a large improvement in performance, the Fluid Combustion Facility (FCF) will house multiple experiments on the International Space Station (ISS). Through a network router located on the spacecraft, individual experiments could be interactively addressed by different ground-based experimenters, with experimental data immediately available to the experimenter. Other ISS experiment modules, Space Shuttle experiments, and scientific spacecraft such as the Hubble Space Telescope are additional examples of in-space Internet connectivity applications. A number of research issues concerning interconnection of orbiting platforms with ground facilities through satellite networks also apply to aeronautical communications networks which in the future will include mobile aircraft acting as internet nodes, an area in which Glenn Research Center also has a significant research program.

The following sections will describe the operational concepts of an Internet-based communications capability for in-space experiment platforms using commercial satellite infrastructure. The key research and technology issues will be identified, and planned approaches for addressing these issues will be discussed.

ARCHITECTURES FOR IN-SPACE INTERNET CONNECTIVITY

A study of the potential application of six current or proposed commercial satellite networks to provide data relay services for low earth orbit (LEO) spacecraft and other space missions showed that a large range of maximum daily data throughput, from 1.5 Mbits to 288 Gbits, could be obtained, depending on the particular satellite network and the space science platform's orbital characteristics[1] . The corresponding average service time per orbit, maximum null time, and user terminal requirements also varied considerably. Hence, fulfilling a particular space science mission need for Internet connectivity to ground users would require consideration of a number of possible commercial satellite solutions, including a combination of two or more satellite networks.

Figure 1 is a depiction of potential connectivity between a user/experimenter on the ground and an orbiting space science platform. Depending on its orbital characteristics, the science platform has the potential to connect to commercial communications satellites in low, medium or geostationary earth orbits (LEO, MEO, or GEO, respectively). LEO or MEO satellites can relay through GEO satellites to ground stations or can connect directly to gateway earth stations. LEO, MEO and GEO constellations may include intersatellite links allowing access to specific earth station locations. Experimenters can access the space science platforms through the gateways using standard terrestrial Internet connections, or more directly using their own dedicated earth station.
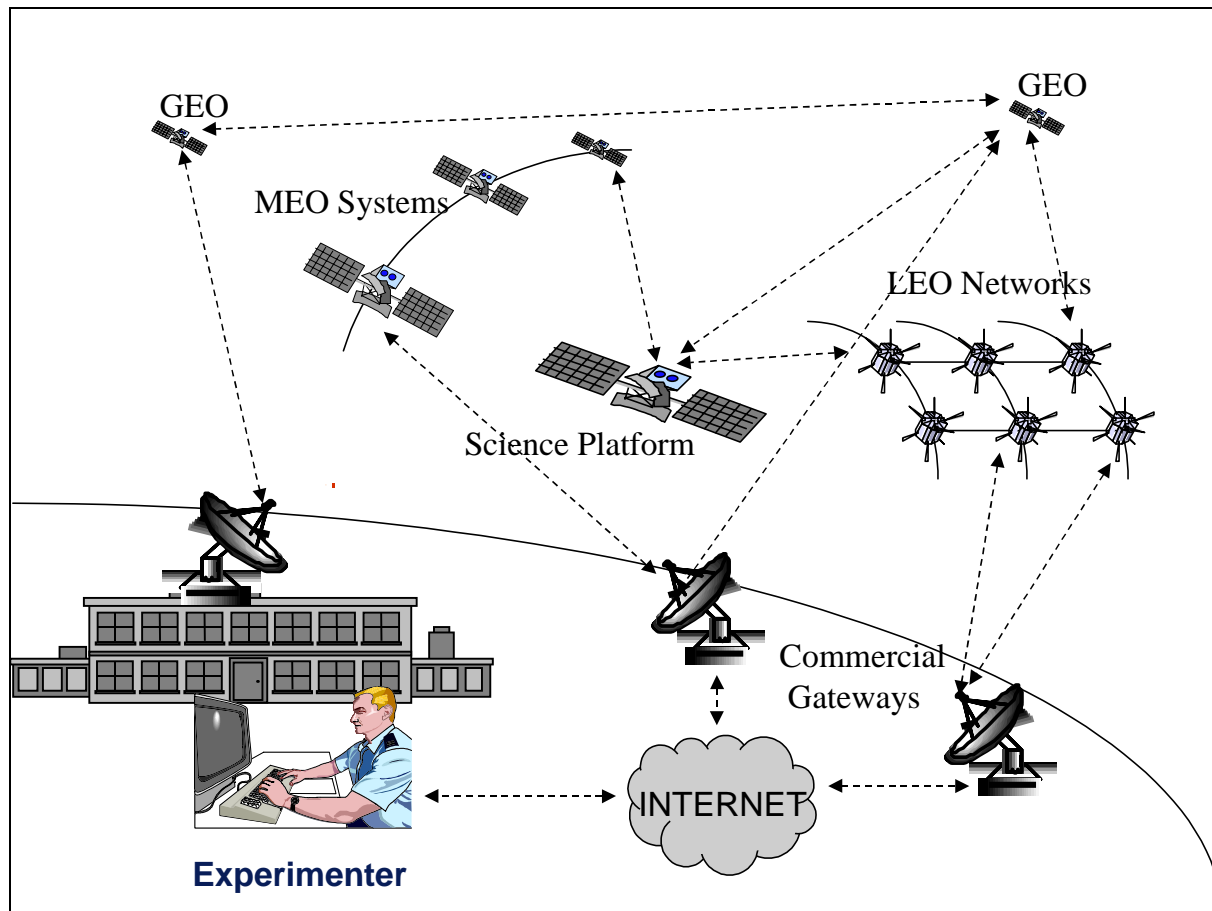

Figure 1 – In-Space Science Platform Internet connections to a Ground Based Experimenter.

The complexity of such architectures ranges from a relatively simple connection of an experimenter to a space science platform through a single GEO spacecraft to a complex connection including a combination of LEO or MEO constellations with intersatellite linking, relays through GEO satellites, and terrestrial Internet connection to a commercial gateway. The simplest architectures will present the fewest implementation problems, but more complex architectures may be required to meet space science mission goals for coverage, connectivity time, and data throughput.

KA BAND IMPLEMENTATIONS

The architectures described above are generic in that they do not include specific existing or planned commercial satellite networks. Many existing or planned satellite networks may be amenable to inclusion in these architectures, regardless of their operating frequency band. However, Ka-Band satellite networks have several potential advantages over lower frequency band satellites for the application being discussed.

A primary advantage of Ka-band is the availability of frequency spectrum adequate for high data rate links. Lower frequency band satellites generally have less available bandwidth and are currently fairly congested with other applications. A second advantage of Ka-band is that hardware is smaller and lighter than for lower bands, reducing the cost of placing science spacecraft in orbit.

Perhaps the most important potential advantage of Ka-band satellite networks is that none have yet been built or deployed. More advanced technology, especially satellite payload designs which are intended for Internet connectivity, is available for these next-generation systems. The potential therefore exists to make great use of commercial satellites that are being designed for Internet usage in creating Internet type connectivity to space science platforms.

RESEARCH AND TECHNOLOGY ISSUES

Operation of an Internet-like network in a rapidly changing physical environment presents major technical challenges. Depending upon the complexity of the network architecture, significant variations in the total path length between the space science platform and the ground-based experimenter will occur. The relative motion between the orbiting space science platform and the network of commercial communications satellites (LEO, MEO, GEO or combination) combined with the motion of the communications satellites relative to the ground stations can result in potentially complex path length profiles. In addition, hand-offs between communicating spacecraft occur as the commercial satellites come into and move out of view of the space science platform. The frequency of hand-offs could range from several per orbit to several per minute depending on the commercial communications network and network architecture being used.

The path length variations result in a corresponding variation of RF propagation parameters that, in turn, affect the signal quality, bit-error rate, and protocol performance. The two key RF propagation parameters are the signal delay and the signal strength. The variation of signal delay primarily affects the performance of Internet protocols as discussed in the following section. The variation in signal strength, where longer path lengths result in reduced signal strength at both space and ground receivers, creates a corresponding variation in the bit-error rate of the transmitted data. Hence, the longer path lengths induce more errors, requiring more frequent retransmission of data packets and reducing the efficiency of the transmission. Overall network performance will vary in a complex fashion, and understanding these variations and designing the network architecture to accommodate them is important in meeting the goals of the space science mission.

Advanced hardware technology required for an in-space Internet network includes primarily space-based tracking antennas and routers. Multi-element phased array antennas which can electronically steer to acquire and track moving spacecraft, and rapidly re-acquire new spacecraft during hand-offs must be made as small, lightweight and affordable as possible. Active phased arrays based on monolithic microwave integrated circuit (MMIC) and other technologies are being developed and tested for these applications under programs sponsored by NASA Glenn. The tracking accuracy of antennas can affect the RF link performance, inducing additional errors and gaps in connectivity and must be accurately understood in order to evaluate the potential per-formance of the network.

Network routers, performing functions similar to high-speed routers that currently provide the switching functions for the Internet, must be developed for use in space in order to achieve a true Internet type network in space. The routers must be small, lightweight, low power and radiation tolerant to enable an efficient and cost effective space network. NASA Glenn Research Center is beginning a program to develop routers for space applications that are compatible with the com-mercial Internet.

PROTOCOL ISSUES

Today's terrestrially based Internet network components generally remain fixed, relative to each other. However, in moving from a terrestrially based network toward including space-based nodes, routers, etc., one starts exercising the limits of the protocols developed for a terrestrially based network. Two distinct protocol areas that are the focus of NASA Glenn's research are transport protocols and routing protocols.

In the transport protocols area, the main focus is on TCP (Transmission Control Protocol)[2], since the reliability and congestion control portions of this protocol are linked to the delay and bit-error rate of the network. The effects of TCP over a ground-to-GEO satellite-to-ground link have been well documented[3]. However, when the delay is not fixed, for instance, in a ground-to-GEO satellite-to-LEO satellite link, the varying delay may have an effect on the performance of TCP. If the round-trip-time (RTT - time for data to be sent from the source computer to the destination computer plus the time for the acknowledgment of the received data to be returned to the source computer) changes too rapidly, TCP may assume a piece of data has been lost, when in fact the acknowledgment for the data is on its way back. Such actions would greatly decrease the efficiency of transmission and reduce network performance. Research is being conducted to determine protocol adaptations that can accommodate the delay variations expected in a complex space-based network and improve overall network performance.

The second area of study involves Internet routing protocols. Due to the movement of satellites, relative to each other, there are times when a line-of-sight connection cannot be maintained be-tween the two objects. Consider the simple case of a LEO communicating through a GEO to the ground. In this scenario, when line-of-sight communication is lost to the GEO, the satellite either must establish a connection to another GEO satellite, on the other side of the earth, or wait until it passes around the earth to reacquire the previously lost GEO. In this case, changes in the routing of packets may need to be made, in order to allow the LEO to start transferring data over this new link. If the scenario is changed to communications between two LEO satellites, the routing must be changed more often to keep relatively constant communication between the

objects. This may include the two LEO satellites communicating over the same GEO satellite or grow to a LEO-to-GEO-to-ground station-to-terrestrial Internet-to-ground station-to-GEO-to-LEO connection. In this case there is a potential of multiple routing changes taking place in a single orbit, with periods of outages or data lost due to packet corruption, re-ordering, duplication, etc., during hand-offs, which decrease the performance of the transport protocol and degrade the performance of the network.

Figure 2 displays the round trip times for communications in a typical LEO-GEO-LEO scenario. Round-trip time (RTT) delays are graphed versus one orbit of time (approximately 101 minutes) between two hypothetical LEO satellites, over one or more GEO satellites. Lower RTTs occur when the two LEO satellites are within line-of-sight of the same GEO satellite. Higher RTTs occur when the LEO satellites are communicating over different GEO satellites, and must be patched together using a link between terrestrial ground stations. There are two loss of signal (LOS) periods in this particular orbit, when either one or both of the LEO satellites are not within line-of-sight of a GEO satellite. These routing problems grow with the size of the constellation. NASA Glenn is researching new routing protocols, based on predictions of satellite movements, to combat this routing problem.
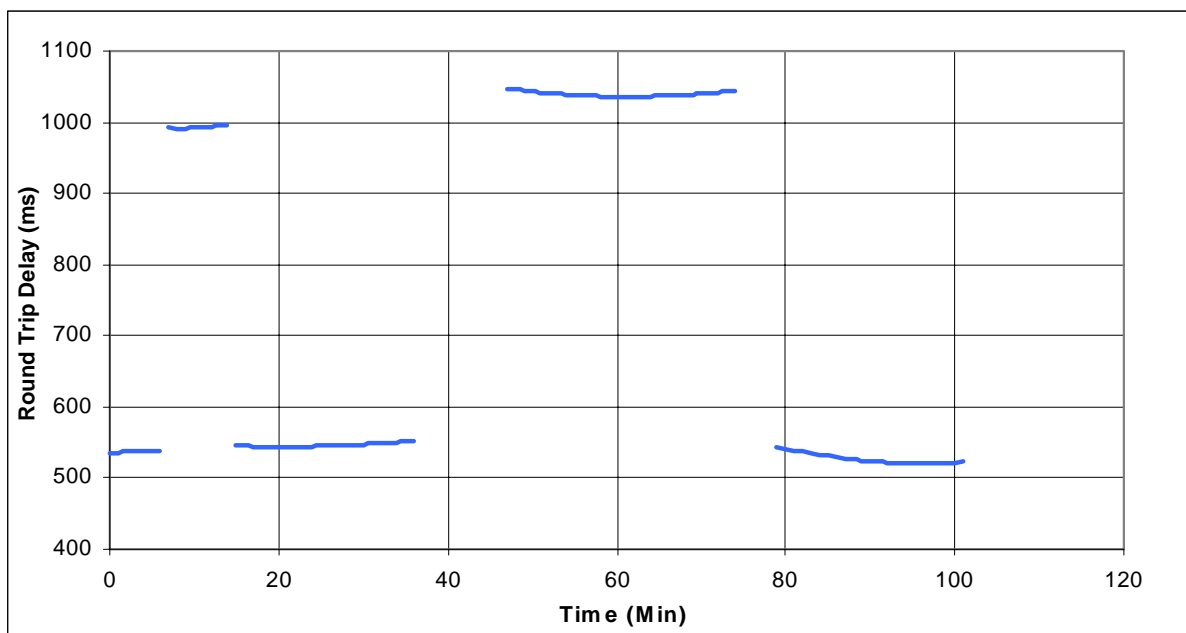

Figure 2 – Hypothetical RTT Delays Between Two LEOs Communicating Over One or More GEOs

THE IN-SPACE INTERNET NODE TESTBED FACILITY

The In-Space Internet Node Testbed (ISINT) is a modular emulator of a RF satellite system, combined with data terminals, routers and Internet network elements to create a simulator/testbed for investigation and research of space-based Internet networks. ISINT also contains interfaces to actual satellite links, such as NASA's Advanced Communications Technology Satellite (ACTS). Figure 3 is a functional block diagram of the testbed. It is a part of the satellite communications research facilities at NASA Glenn Research Center. The facility is configurable to enable the emulation of a variety of satellites, constellations, and combinations of space network elements.
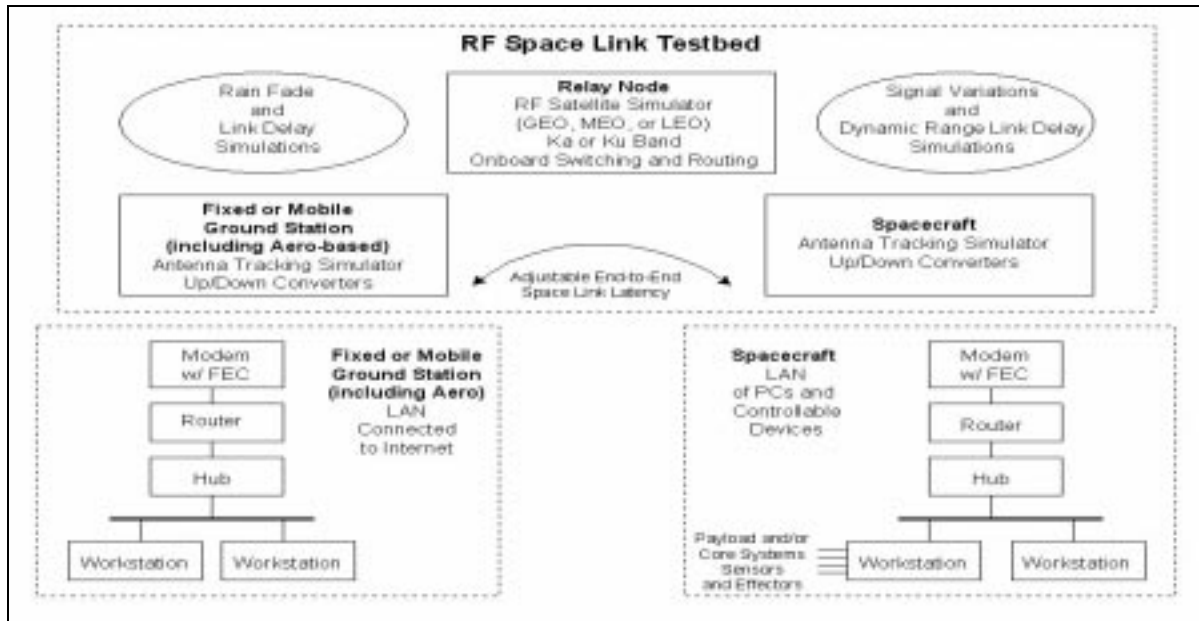
Figure 3 – ISINT Functional Block Diagram

The main component of the ISINT facility is the ACTS proof of concept model, which mirrors the functionality of the ACTS satellite[4]. Dynamic range link delay, the enhancement that allows emulation of moving satellites is done via a modified version of the Ohio Network Emulator software (ONE)[5]. The ONE software monitors the link, and all packets on it are brought into a buffer. By holding those packets for a fixed length of time, the delay function is achieved. When the fixed time expires, the packet is released from the buffer and sent out the other network interface. By reading values from a predefined data set with orbital characteristics of a satellite constellation, the desired delay is infused into the emulation. Effectively, this allows for a variable delay. The data set contains information on how long each delay should be, and at what rate each delay should be changed.

Typical signal variations for a LEO spacecraft communicating via a GEO satellite are shown in Figure 4, which is based on a simulation of a Space Shuttle communication link through a Tracking and Data Relay Satellite (TDRS). The signal variation depicted can result in a bit-error rate variation of up to six orders of magnitude, hence accurate simulation of this parameter is essential. Signal variation is modeled by varying the power received at the modems. Configurable computer software facilitates automated signal power variation within the RF links of the ISINT testbed. User defined orbit data sets create a representation of the signal variation experienced by a spacecraft to communication satellite link. By changing the data sets, the complexion of the emulation can be varied to implement rain fade, antenna acquisition and tracking models, satellite constellations, and architectural scenarios.

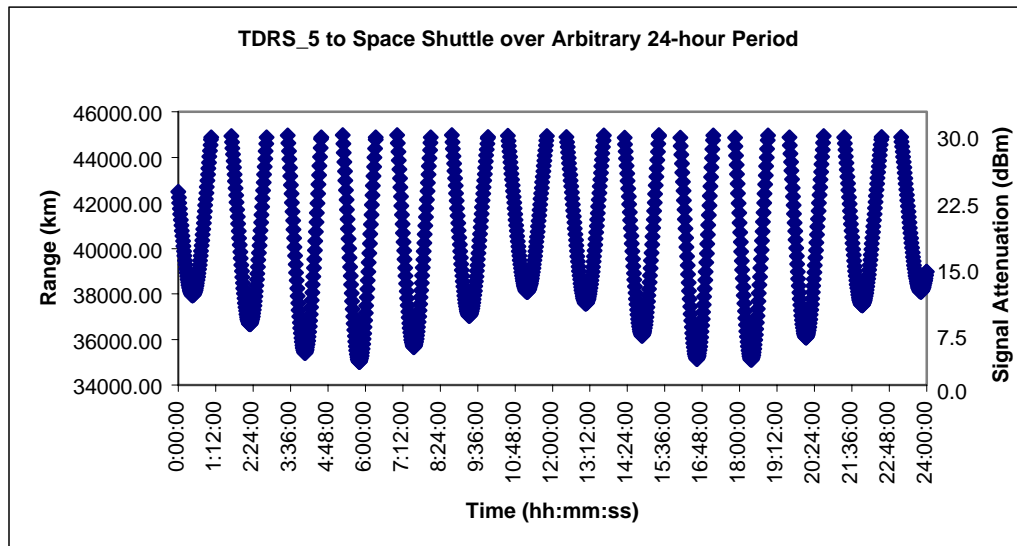**TDRS_5 to Space Shuttle over Arbitrary 24-hour Period**

Figure 4 – Typical Signal Variation

As use of the Internet increases, there is an ever-increasing demand for more bandwidth over which to communicate. As previously discussed, Ka-band satellites can provide the needed bandwidth, but standard Internet protocols have not been sufficiently tested over high speed, long and variable latency links. Testing over the ISINT facility has begun using a single T1 link over both the RF testbed and over an actual ACTS link, with future experiments expanding to higher data rates. 30 transfers of each file size (50 kbytes, 750 kbytes, 30 Mbytes, and 50 Mbytes) were sent over ACTS and over the Ka-band RF testbed from a simulated "space node" to a "terrestrial node." Although this type of point to point communication over a GEO transfer link is well understood, it is useful to validate the configuration of the testbed before more complex architectures are pursued. Analysis of the file transfer times found that there was less than 1% difference between files transferred over ACTS versus over the ISINT facility for file sizes greater than 1 Mbyte [4].

Verification of the testbed's throughput performance compared to ACTS throughput was the first step toward testing the more complex architectures and link paths discussed previously. Testing using variable range delay has just begun. Future tests will validate the use of Internet protocols over OC-1 and OC-3 satellite links. Although the need of 52 Mbps and 155 Mbps channels for Internet traffic seems inconceivable today, a quick review of the growth of the Internet over the past 10 years indicates a likely need for more bandwidth and faster devices. Undoubtedly, Space Shuttle, ISS, and eventually other science spacecraft will need this kind of speed and bandwidth also.

Additional long-term plans for the ISINT facility involve investigations into the feasibility of using Point-To-Point Protocols (PPP) over variable delay satellite networks and into the effects of the delay on remote control of instruments and devices.

SUMMARY

The rapid advance of space communications and internet technologies can be harnessed to provide significantly better performance and lower costs for future space-based science experiments and other space missions. In particular, Internet methods can allow ground based experimenters direct control of orbiting experiments, greatly improving the value of space science platforms, using commercial and especially Ka Band satellite networks. However, meeting mission needs and optimizing experimental value may require complex space network architectures. To enable efficient performance of such networks, the NASA Glenn Research Center is performing research on critical protocol and technology issues. Using testbed and satellite experiments and laboratory simulations such as the ISINT facility, NASA is developing approaches and technologies that will allow standard Internet techniques to be applied to control of future space science mission experiments and collection of resulting data.

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Robert J. Kerczewski, Kul B. Bhasin, Theodore P. Fabian, James H. Griner, Brian A. Kachmar and Alan M. Richard

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National Aeronautics and Space Administration
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